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On the production of very high energy beamed gamma-rays in blazars

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Abstract. The variable flux of TeV gamma-rays detected from Mkn 421 and Mkn 501 requires the presence of high energy electrons, which could in principle produce large numbers of electron/positron pairs, leading to an electromagnetic cascade. We point out that this scenario can be avoided if electrons are accelerated to high energy rectilinearly, rather than being injected isotropically into a blob, as in most of the models of the GeV gamma-ray emission. By balancing linear acceleration by an electric field against inverse Compton losses in the radiation field of the accretion disk we calculate the emitted spectra and find the conditions which must be fulfilled in order to exclude the development of electromagnetic cascades during acceleration. Assuming these to be fulfilled, we show that the maximum possible photon energy is approximately $10M_8^{2/5}$ TeV, where M_8 is the mass of the central black hole in units of $10^8\,M_\odot$. In addition we compute the optical depth to absorption of TeV photons on a possible isotropic scattered component and on the observed nonthermal radiation (in the case of Mkn 421) and find that TeV photons can escape provided the nonthermal X-rays originate in a jet moving with a Lorentz factor $\gamma_{\rm b} \gtrsim 8$.

Key words: acceleration of particles – Accretion, accretion disks – Galaxies, active – BL Lacterae objects: Mkn 421, Mkn 501 – Gamma rays: theory

1. Introduction

Gamma-rays of energy up to 10 GeV have been observed from many active galactic nuclei by the EGRET experiment on the Compton Gamma-Ray Observatory (von Montigny et al. 1995). Although hadronic models have been proposed (Mannheim & Biermann 1992) most models assume the gamma-rays are produced by inverse Compton scattering off electrons contained in a blob of plasma which itself is in relativistic motion in the general direction of the observer (Maraschi et al 1992; Dermer & Schlickeiser 1993; Blandford & Levinson 1995). These models differ in their assumptions about the soft target photons (Schlickeiser 1996), but they all assume the electrons to be isotropically distributed in the rest frame of the blob. The gamma-ray luminosity they predict is relativistically boosted, so that the observer receives a flux which exceeds that measured in the rest frame of the blob by several orders of magnitude.

In the TeV regime two blazars – Mkn 421 and Mkn 501 – have been observed to emit gamma-rays of energy $\gtrsim 4$ TeV (Punch et al. 1992, Quinn et al. 1995). Of those, Mkn 421 is also an EGRET source and its spectrum is consistent with an unbroken power law spectrum of photon index $\simeq -2$ between GeV and TeV energies, which makes it unlikely that these photons have been reprocessed by an electromagnetic cascade. Electrons of Lorentz factor exceeding 10^6 are required in the blob frame in order to explain the observations, and, if isotropically distributed, these would inevitably undergo photon scattering events well into the Klein-Nishina regime. Such events produce pairs, either directly via the triplet pair production process (Mastichiadis 1991) or indirectly via photon-photon pair production. Thus, although there are no detailed calculations of the development of a cascade in the anisotropic radiation field seen by a relativistic blob, a problem is quite likely to arise.

In view of this, we present here a model in which electrons are accelerated to high energies rectilinearly in an electric field. For certain values of the potential, acceleration can be balanced by inverse Compton scattering on the accretion disk photons which occurs in the Thomson regime, thus avoiding the problem of a cascade. Since we are interested in the outgoing gamma radiation, we follow electrons which propagate outwards and calculate their energy as well as that of the associated photons as a function of height above the accretion disk. Adopting a simple

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model for the disk radiation we find that close to the disk, Thomson losses limit the particle energy to a relatively small value, whereas far from it the losses are smaller and particles reach higher energies before their acceleration is saturated. Lower energy gamma rays thus originate close to the disk whereas photons of TeV energy come from a distance of about 1000 gravitational radii away from the black hole.

The system of a jet emerging along the rotation axis of an accretion disk which underlies our calculations is described in Sect. 2. The saturation of electron acceleration by inverse Compton scattering and the resulting spectrum is computed in Sect. 3. In the same Section we give also the necessary conditions which make the inverse Compton scattering to occur in the Thomson regime. Finally we discuss the implications of our model in Sect. 4

2. The disk/jet geometry

We adopt a simple one-dimensional model of a jet in which there are localised regions where particles can be accelerated by an electric field. There are several ways of realising such a configuration. Magnetic reconnection (e.g., Schindler et al 1991, Haswell et al 1992) leads to potential drops aligned along the magnetic field, but is amenable only to rough estimates. Almost rectilinear acceleration can occur for some trajectories as a result of an encounter with a relativistic oblique shock front, such as may be expected within a relativistic jet (Begelman & Kirk 1990) and is an integral part of the 'surfatron' process (Katsouleas & Dawson 1983) which has as yet not been applied in an astrophysical context. Alternatively, an electric field component along the jet axis may be induced close to the black hole (Blandford & Znajek 1977, Macdonald & Thorne 1982, Bednarek & Kirk 1995) or arise in the sheath between a relativistic jet and its surroundings (Bisnovaty-Kogan & Lovelace 1995).

The orientation of accelerating regions is important for the computation of the losses suffered by the particles. We will assume it to be along the jet axis. The maximum potential which can be realised within an acceleration region scales with the local magnetic field strength and the coherence length scale of the region. For a constant opening angle of the jet, the dominant magnetic field component falls off inversely as the distance $zr_{\rm g}$ from the black hole. Here $r_{\rm g}$ is the gravitational radius $r_{\rm g} = 2GM_{\rm BH}/c^2$ of a black hole of mass $M_{\rm BH}$. In this case, the coherence length is likely to be proportional to z, so that the potential available in an acceleration zone is independent of position in the jet (Bednarek et al 1995). In this paper, we treat a more general situation in which the maximum potential ΔV varies inversely as some power α of z, i.e., $\Delta V = V_0 z^{-\alpha}$. The coherence length will be taken to be a fixed fraction β (<1) of the distance from the black hole, so that the electric field is given by $E(z) = V_0 z^{-\alpha-1}/(r_{\rm g}\beta)$. Although it is to be expected that the jet moves relativistically with bulk Lorentz factor ~ 10 we assume the acceleration zones to be stationary in the 'lab.' frame, as would be expected if they are associated with shock fronts caused by an obstacle at the edge of the jet. The particle dynamics are then described simply in terms of the electric field, and have no superimposed bulk motion until they have emerged from an acceleration zone and have had enough time to isotropise.

The radiation fields which may be present and lead to inverse Compton losses are of two different kinds - an ambient almost isotropic field arising from backscattering of the luminosity of the entire black hole/disk/jet system (Sikora et al 1994, Blandford & Levinson 1995) and an anisotropic component of photons which come directly from the disk. Objects which emit TeV photons must have relatively weak isotropic radiation fields, so that in this paper we will concentrate on the direct radiation from the disk (see Sect. 4). An important property of an accretion disk is that its surface temperature falls off with increasing radius r. To include this effect we adopt a Shakura/Sunyaev profile and assume the disk emits blackbody radiation at temperature $T(r) = T_{\rm in}(r_{\rm in}/r)^{3/4}$ where $T_{\rm in}$ is the temperature at the inner edge of the disk assumed to lie at $r = r_{\rm in} = 3r_{\rm g}$. Thus, two parameters are required to specify the disk, and these we choose to be the luminosity $\ell_{\rm Edd}$ of the disk in units of the Eddington luminosity: $\ell_{\rm Edd} = 1.5 \times 10^{-35} T_{\rm in}^4 r_{\rm g}$ and the mass M_8 of the black hole, expressed in units of $10^8\, M_\odot$.

3. Inverse Compton scattering

The Lorentz factor of electrons accelerated rectilinearly by the electric field described in Sect. 2, is limited under certain conditions by Compton scattering. The radiation responsible for this can in principle either come directly from the disk, or have been scattered by surrounding material into a quasi-isotropic distribution. The Thomson losses of a particle moving along the jet axis in the anisotropic radiation field of the disk are straightforward to compute e.g., by generalising the results of Protheroe et al (1992):

$$\dot{\gamma} = 0.25 \times \gamma^2 \ell_{\rm Edd} M_8^{-1} z^{-3}\ {\rm s}^{-1}\ . \quad (1)$$

Using this formula, one finds that losses balance gains in the electric field at an equilibrium Lorentz factor given by

$$\gamma_{\rm eq}(z)\ =\ 8.82 \times 10^{-5} V_0^{1/2} z^{-\alpha/2+1} \beta^{-1/2} \ell_{\rm Edd}^{-1/2} \quad (2)$$

where V_0 is measured in volts. Losses on the isotropic radiation field depend on the radius typical of the scattering material $R_{\rm sc}$ and on its optical depth $\tau_{\rm sc}$. We find that disk radiation dominates the energy losses for distances

$$z\ \lesssim\ 8000 (R_{\rm sc}/1\,{\rm pc})^{2/3} (\tau_{\rm sc}/10^{-3})^{-1/3} M_8^{-2/3}\ . \quad (3)$$

A limit on the column density of matter in Mkn 421 can be obtained from X-ray observations: $n_{\rm H} \leq 1.45 \times 10^{20} {\rm cm}^{-2}$

(Fink et al 1991) corresponding to a Thomson optical depth $\tau_{\rm sc} \leq 10^{-4}$. According to Eq. (3) this means that losses are dominated by the radiation field of the disk.

Equations (1) and (2) are valid provided the electrons scatter in the Thomson regime. Approximating the black-body spectrum by monoenergetic photons of energy $3k_{\rm B}T$, this condition implies the requirement

$$3k_{\rm B}T_{\rm in}z^{-3/4}\left\{(3z/r)^{3/4}\left[1-(1+(z/r)^2)^{-1/2}\right]\right\}\gamma \lesssim mc^2 \quad (4)$$

for photons from a point at radius r on the disk. The quantity in braces on the left-hand side reaches a maximum of roughly 0.7 at $r \approx 2z$, leading to

$$\gamma \ \lesssim \ 1.4\times 10^4 (M_8/\ell_{\rm Edd})^{1/4} z^{3/4} \ . \quad (5)$$

In order to channel energy efficiently into gamma-rays, the potential must accelerate electrons to an energy high enough for losses to be important. If this is not the case, the acceleration process puts energy primarily into particles, which may subsequently isotropise and radiate, as in other models. Thus, the condition $\gamma_{\rm eq}mc^2 = e\Delta V$ separates the region in which energy is put directly into radiation, which we call the 'radiation dominated' zone, from the 'particle dominated zone' where energy is first transferred by the acceleration mechanism into particles, which cool only after acceleration has ceased.

Figure 1 shows the constraints on the parameter space for black-hole mass $M_8 = 1$, disk luminosity $\ell_{\rm Edd} = 0.1$ and $\beta = .1$. In addition, the dependence of $\gamma_{\rm eq}$ on z is shown for various values of the potential V_0 and for $\alpha = 0$.

If a particle is accelerated linearly at a point in the jet within the permitted region lying between the dashed and solid lines in Fig. 1, its equilibrium Lorentz factor is given by Eq. (2). If, however, the electric field is too strong, and the particle finds itself above the Klein-Nishina boundary, the photons it produces will start a pair avalanche similar to that described by Bednarek & Kirk (1995). As a result, we can expect that the particle will not achieve the Lorentz factor given by Eq. (2). On the other hand, a weak electric field places the particle in the particle dominated region. Here the total available potential in an acceleration region is insufficient to produce particles of Lorentz factor given by Eq. (2). Thus, the maximum possible Lorentz factor $\gamma_{\rm max}$ is achieved for jet parameters within the permitted region and at the highest z compatible with this restriction. This value depends only weakly on the mass of the black hole $\gamma_{\rm max} = 1.1\times 10^8 M_8^{2/5}\ell_{\rm Edd}^{1/5}\beta^{3/5}$ and is achieved at a height $z_{\rm max} = 1.6\times 10^5 M_8^{1/5}\ell_{\rm Edd}^{3/5}\beta^{4/5}$.

An analytic expression can be found for the radiated photon spectra in the "radiation dominated" zone using the method of Protheroe et al (1992). The average energy $\epsilon_{\rm av}$ of a photon produced at height z is approximately $\gamma_{\rm eq}^2\epsilon_{\rm s}$, where $\epsilon_{\rm s}$ is the energy of the dominant soft photons, which are those originating at a point on the disk

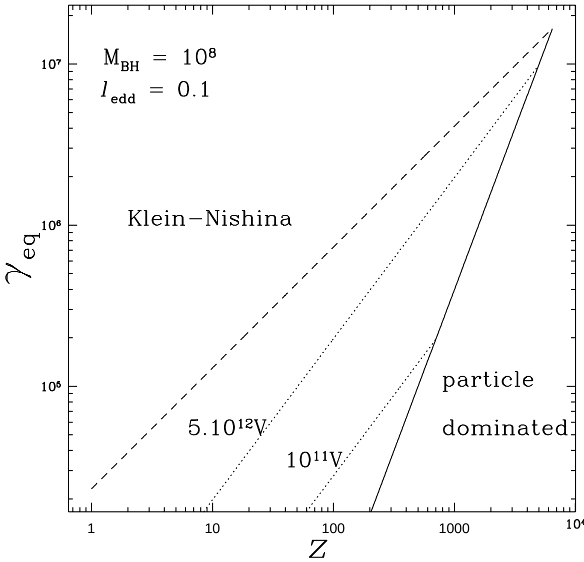

Fig. 1. The parameter space for rectilinear acceleration. The solid line shows the constraint $\gamma_{\rm eq} = e\Delta V/(mc^2)$ dividing radiation and particle dominated zones. The dashed line shows the boundary between the Thomson and Klein-Nishina scattering zones. These boundaries are independent of the dependence of the potential along the jet and are plotted for $\beta = 0.1$. The dotted lines show $\gamma_{\rm eq}$ for $V_0 = 10^{11}$ and $V_0 = 5\times 10^{12}$ V. These lines have the slope $1-\alpha/2$ and are shown for $\Delta V =$ constant, corresponding to $\alpha = 0$.

approximately given by $r = r_{\rm g}z$. Thus, $\epsilon_{\rm s} \propto z^{-3/4}$ and $\epsilon_{\rm av} \propto z^{-\alpha+5/4}$. The energy converted into gamma-rays by a single particle passing through a distance dz is equal to the energy extracted from the electric field. If dn photons are thereby produced, one can write $\epsilon_{\rm av}{\rm d}n = ec\,E(z){\rm d}z \propto z^{-\alpha-1}{\rm d}z$. As shown by Protheroe et al (1992) the photon spectrum dn/dϵ can be found by convolving dn/d$\epsilon_{\rm av}$ with the real distribution $p(\epsilon,\epsilon_{\rm av})$ of emitted photons. For the cases which are of interest here, however, this does not affect the spectral slope, which is given by

$$({\rm d}n/{\rm d}\epsilon) \ \propto \ \epsilon^{-(4\alpha-10)/(4\alpha-5)} \ . \quad (6)$$

If we assume equal numbers of particles are present in the acceleration zones over a range of heights $z_1 < z < z_2$, then we obtain a power-law spectrum between the photon energies $\epsilon_1 = \epsilon(z_1)$ and $\epsilon_2 = \epsilon(z_2)$ where

$$\epsilon(z) \ \simeq \ 1.9\times 10^{-7} V_0\,\ell_{\rm Edd}^{-3/4} M_8^{-1/4}\beta^{-1} z^{-\alpha+5/4} \ {\rm eV} \ . \quad (7)$$

For $\alpha = 0$, a spectrum of index -2 is obtained. The maximum possible photon energy is then

$$\epsilon_{\rm max} \ \simeq \ 3.4\times 10^{13}\beta^{3/5}\ell_{\rm Edd}^{1/5} M_8^{2/5} \ {\rm eV} \ . \quad (8)$$

4. Discussion

In our model, the gamma radiation observed from blazars is produced by electrons subject to rectilinear acceleration which is balanced by losses due to inverse Compton scattering on accretion disk photons. In this case, the TeV γ-ray emission from an object such as Mkn 421 originates in the upper part of the radiation dominated zone of the jet at a distance of about 1000 gravitational radii from the black hole. If the disk radiation dominates over that of the isotropic component at even larger distances ($z \approx 6000$), the maximum achievable photon energy for $\beta \approx \ell_{\rm Edd} \approx 0.1$ is about 10 TeV.

There are two interesting features of the proposed model. Firstly, the inclusion of an explicit acceleration mechanism leads naturally to a prediction of the site at which high energy gamma rays are produced. Secondly, the fact that the electron-soft photon collisions occur in the Thomson regime guarantees that the resulting gamma rays are emitted below the threshold for pair production, thus avoiding the complications of an electromagnetic cascade.

However, severe additional constraints must be fulfilled if these photons are to leave the source and avoid absorption on other ambient radiation fields. Two types of field are important: (i) an isotropic component arising from scattered disk radiation and (ii) the observed nonthermal radiation. Of these, (i) is not directly observed in the blazars of relevance here. Thus, there is little information concerning how much matter surrounds the accretion disk (such as column density or typical distance scale). Detailed computations of the optical depth for γ-ray photons escaping from the accretion disk in Mkn 421 have been performed by Böttcher & Dermer (1995). However, these authors assume a Thomson optical depth around the disk of 0.02 out to a distance of 0.1 pc. This is consistent with ROSAT observations (Fink et al 1991) only if the X-rays are produced at $zr_{\rm g} > 0.1$ pc. If, as we assume, this is not the case, $\tau_{\rm sc} < 10^{-4}$ and the absorption of TeV γ-rays by the isotropic component (i) is negligible.

In case (ii), the nonthermal radiation is directly observed. According to our model, these photons are produced in the particle dominated zone at $z > 1000$ where the electrons have time to isotropise and form a relativistic radiating blob as in other models of the GeV gamma-ray emission. The optical depth to absorption of the TeV gamma-rays in such a blob is given by

$$\tau(\epsilon) \ = \ \frac{16D^2}{\gamma_{\rm b}^2 R_{\rm b} c} \int {\rm d}\epsilon_{\rm b} \int {\rm d}(\cos\theta_{\rm b})\, F(2\gamma_{\rm b}\epsilon_{\rm b}) \\ \times \ (1-\cos\theta_b)\sigma_{\gamma\gamma}[\epsilon/(2\gamma_{\rm b}), \epsilon_{\rm b}, \theta_{\rm b}] \ , \qquad (9)$$

where D is the distance to Mkn 421, $R_{\rm b}$ is the radius of the blob, $F(\epsilon)$ is the observed photon flux at energy ϵ [which we approximate as a power law with index -2 below and -2.4 above 10^{-4} MeV, with a normalisation taken from the observations (Fink et al 1991, Makino et al 1987)] and $\sigma_{\gamma\gamma}(\epsilon, \epsilon', \theta)$ is the cross section for $e^{\pm}$ pair production of a photon of energy ϵ off one of energy ϵ' with θ the angle between the directions of travel (Jauch & Rohrlich 1955).

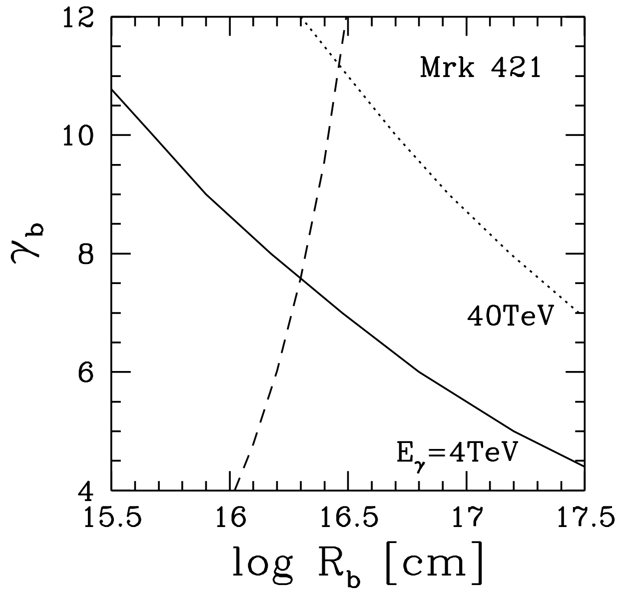

Fig. 2. The requirements for escape of 4 TeV and 40 TeV γ-rays through the nonthermal radiation of a relativistic blob in Mkn 421. The Lorentz factor γ_b and radius R_b of a radiating blob above which the optical depth for 4 TeV (full line) and 40 TeV (dotted line) γ-rays is less than unity. The dashed line shows the minimum $\gamma_{\rm b}$ which permits an X-ray variability time scale of one day.

The full line in Fig. 2 shows the parameters of the blob in Mkn 421 ($\gamma_{\rm b}$, $R_{\rm b}$) for which the optical depth for 4 TeV γ-rays is equal to unity. An additional constraint on the Lorentz factor of the jet arises from the X-ray variability time scale $t_{\rm var} \approx 1$ day (e.g. Fink et al 1991). Assuming that the blob moves directly towards the observer we find

$$\gamma_{\rm b} \ > \ R_{\rm b}/ct_{\rm var} \ > \ 3.8\times 10^{-16} R_{\rm b} \ [{\rm cm}] \ , \qquad (10)$$

which is shown in Fig. 2 by the dashed line. The region in Fig. 2 above the full and dashed lines gives the permitted parameters of the blob in Mkn 421 for which the γ-rays with maximal energy of 4 TeV can escape. From it we may also constrain the Lorentz factor of the blob: $\gamma_{\rm b} > 7.5$. For reasonable values of $\gamma_{\rm b}$ (of the order of tens) and an opening angle of the jet of the order of a few degrees (which determines $R_{\rm b}$), the blob is located inside the particle dominated zone of the jet, in agreement with our assumptions.

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References

Bednarek, W., Kirk. J.G. 1995, A&A 294, 366

Bednarek, W., Kirk, J.G., Mastichiadis, A. 1995, Proc. 24th ICRC (Rome), 2, 295
Begelman, M.C., Kirk, J.G. 1990, ApJ 353, 66
Bisnovaty-Kogan, G.S., Lovelace, R.V.E. 1995, A&A 296, L17
Blandford, R.D., Levinson, A. 1995, ApJ 441, 79
Blandford, R.D., Znajek, R. 1977, MNRAS 179, 433
Böttcher, M., Dermer, C.D. 1995, A&A, 302, 37
Dermer, C.D., Schlickeiser, R. 1993, ApJ 416, 458 ("DS")
Fink, H.H., Thomas, H.-C., Hasinger, G. et al. 1991, A&A 246, L6
Haswell, C.A., Tajima, T., Sakai, J. 1992, ApJ 401, 495
Jauch, J.M., Rohrlich, F. 1955, The Theory of photons and electrons (Addison-Wesley)
Katsouleas, T., Dawson, J.M. 1983, Phys. Rev. Letts. 51, 392
Macdonald, D., Thorne, K.S. 1982, MNRAS 198, 345
Makino, F. et al. 1987, ApJ 313, 662
Mannheim, K., Biermann, P.L. 1992, A&A 221, 211
Maraschi, L., Ghisellini, G., Celloti, A. 1992, ApJ 397, L5
Mastichiadis, A. 1991, MNRAS 253, 235
Protheroe, R.J., Mastichiadis, A., Dermer, C.D. 1992, Astropart. Phys. 1, 113
Punch, M. et al. 1992, Nature 358, 477
Quinn, J. 1995, IAU Circ., No. 6169
Schindler, K., Hesse, M., Birn, J. 1991, ApJ 380, 293
Schlickeiser, R. 1996, Space Science Reviews, in press
Sikora, M., Begelman, M.C., Rees, M.J. 1994, ApJ 421, 153
von Montigny, C., Bertsch, D.L., Chiang, J. et al. 1995, ApJ 440, 525

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